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Title: Quantum computing using ultracolde neutrons (UCN)

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Quantum computing

using ultracold neutrons (UCN)

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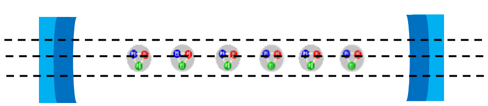
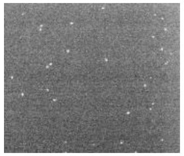
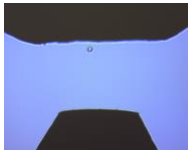
Oct. 23, 2019

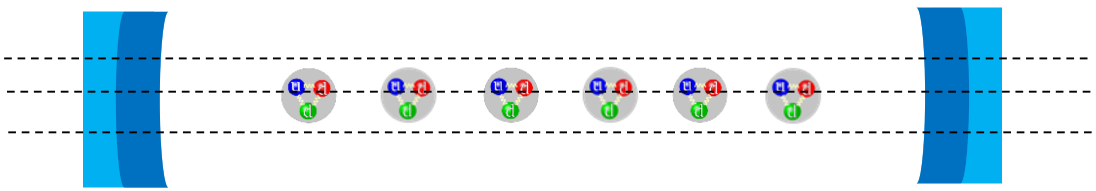
Supported by FY2019, RR on novel computing

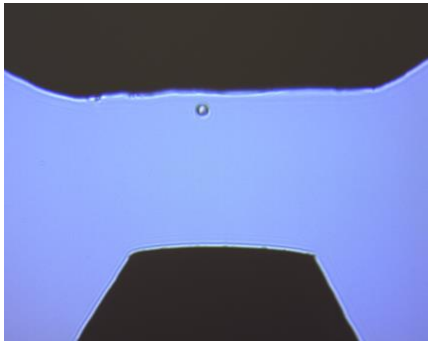


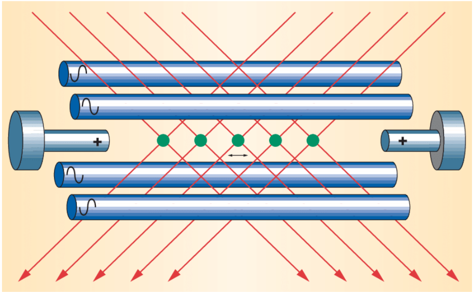




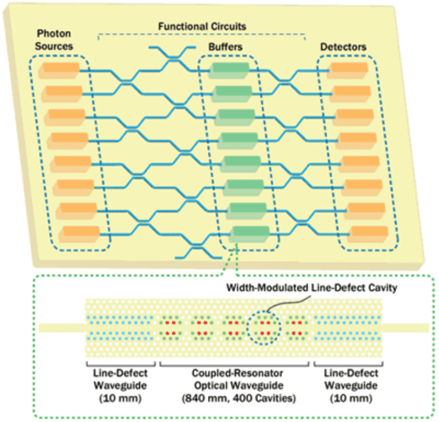
A UCN quantum computer (QC) concept



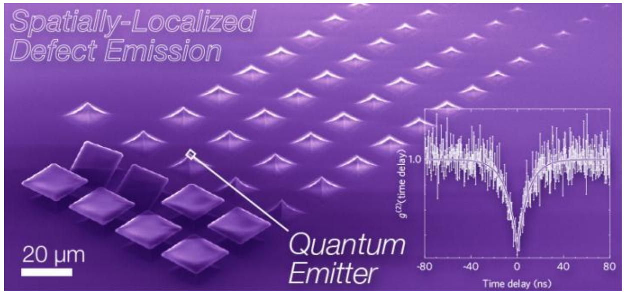




Steane & Rieffel, Computer (2000)

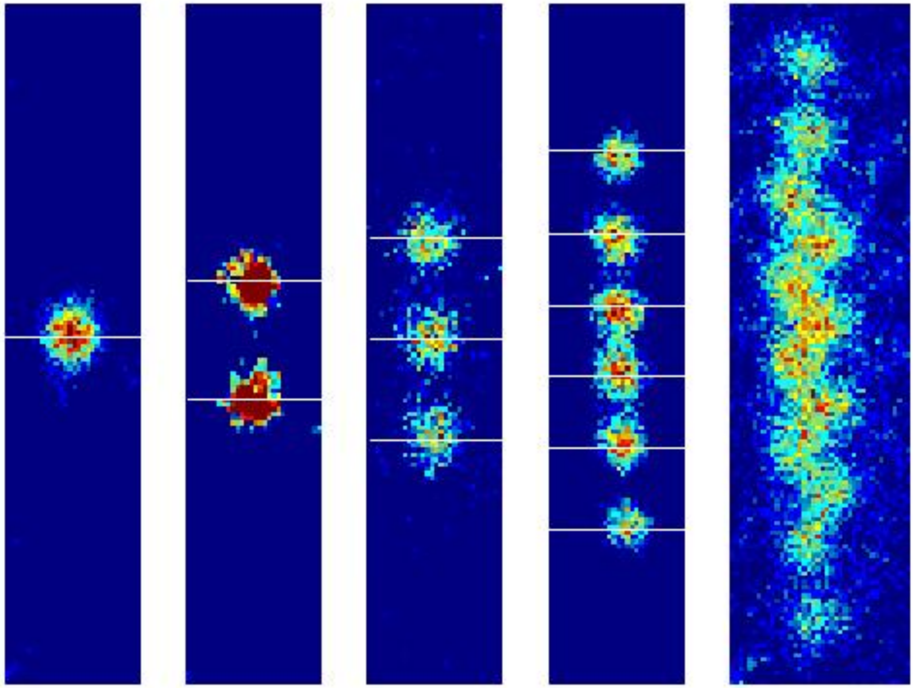


Takesue et al. SR 4 (2014)



Wu et al, APL 114 (2019)

Development path



1, 2, 3, …

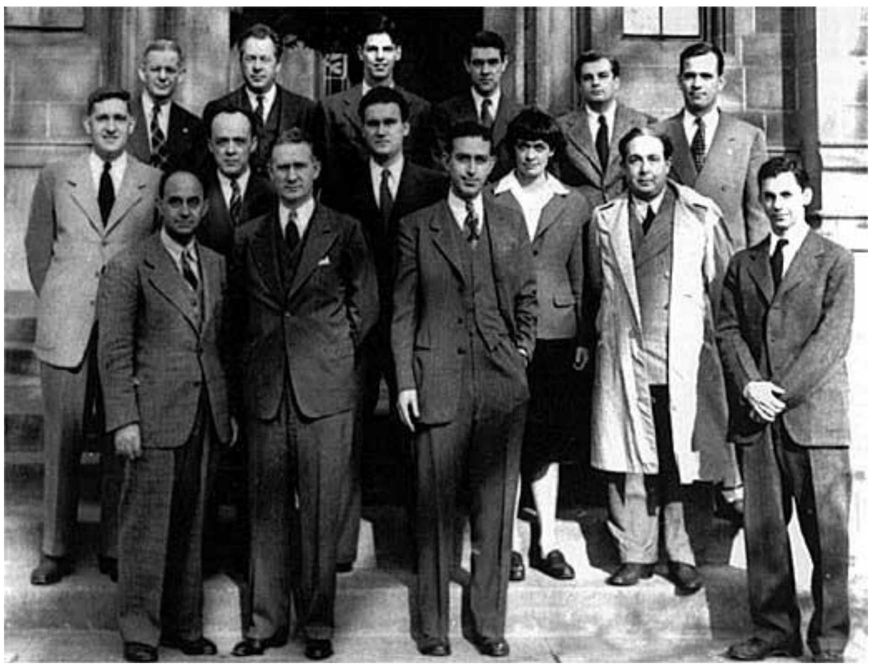
Seidelin et al, PRL 96, 253003 (2006)

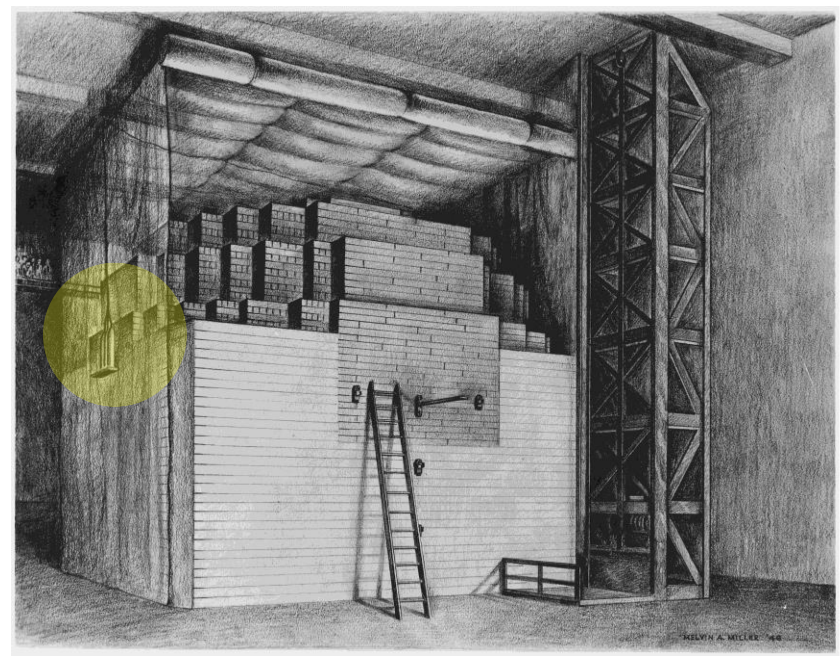
Outline

- Background
- DiVincenzo criteria for UCN QC
- UCN trapping & entanglement
- UCN source & detection

Fermi & neutron science

On Dec. 2, 1942, Fermi & his team achieved sustained chain reaction, and the first fission reactor. Key elements: fuel, neutron moderator, control rod, neutron detector, and radioactivity detector.





Chicago Pile-1 (CP-1)

Neutron & the standard model of particles

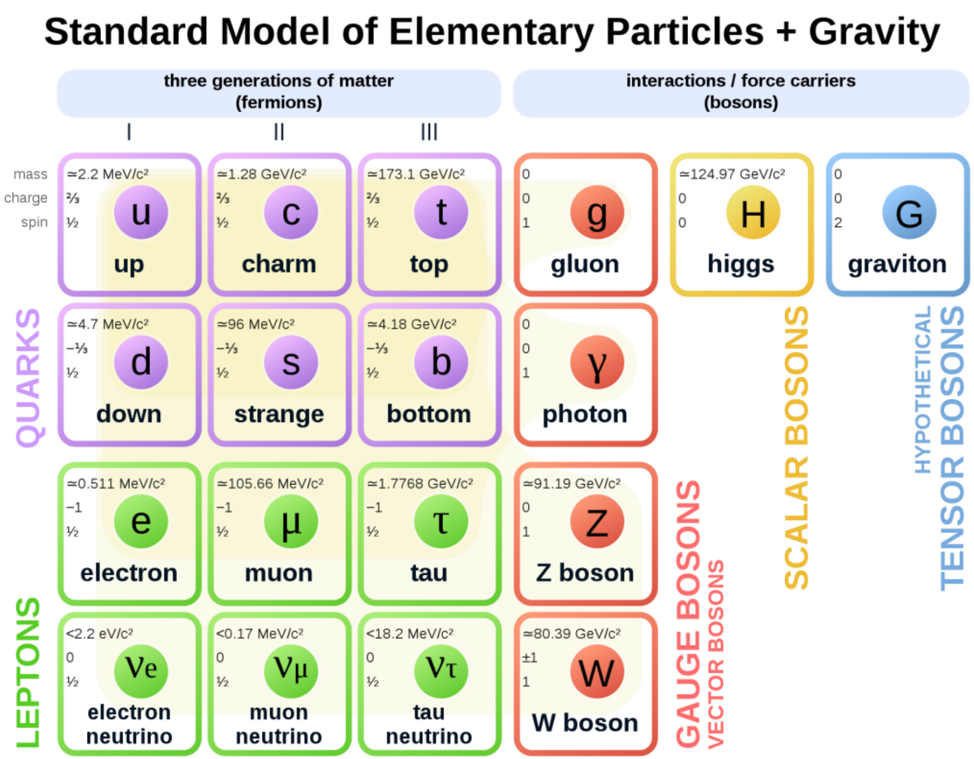
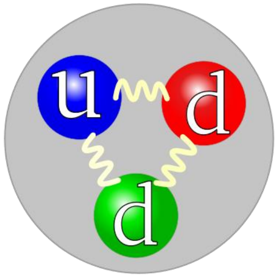
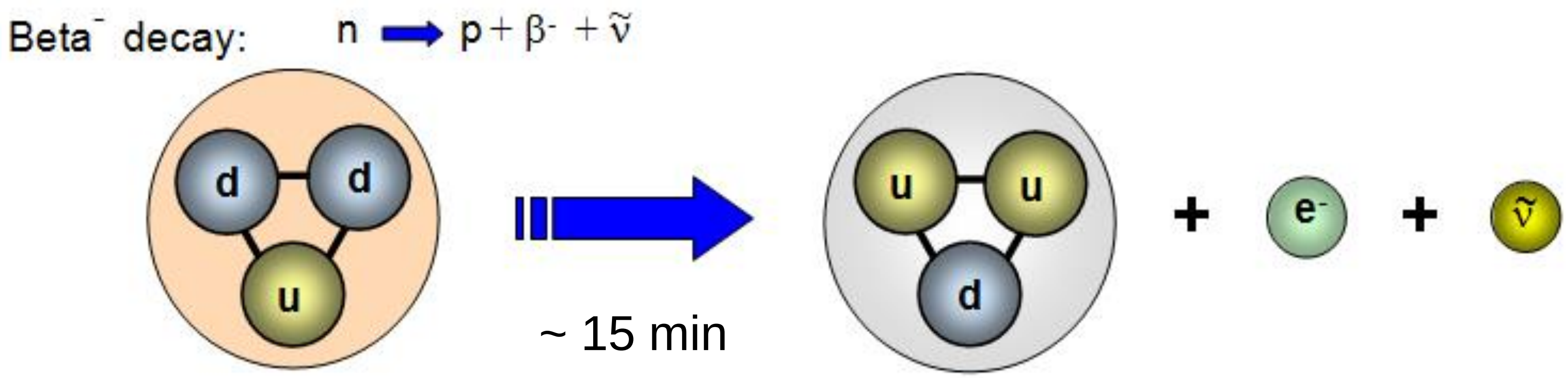


Image credit: Wikipedia/ WWW resources

A neutron

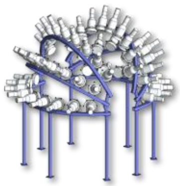


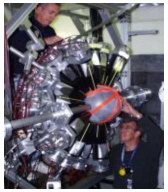
Physics beyond the standard model : Neutron approach

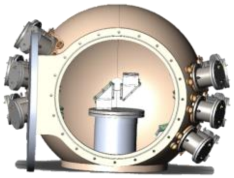


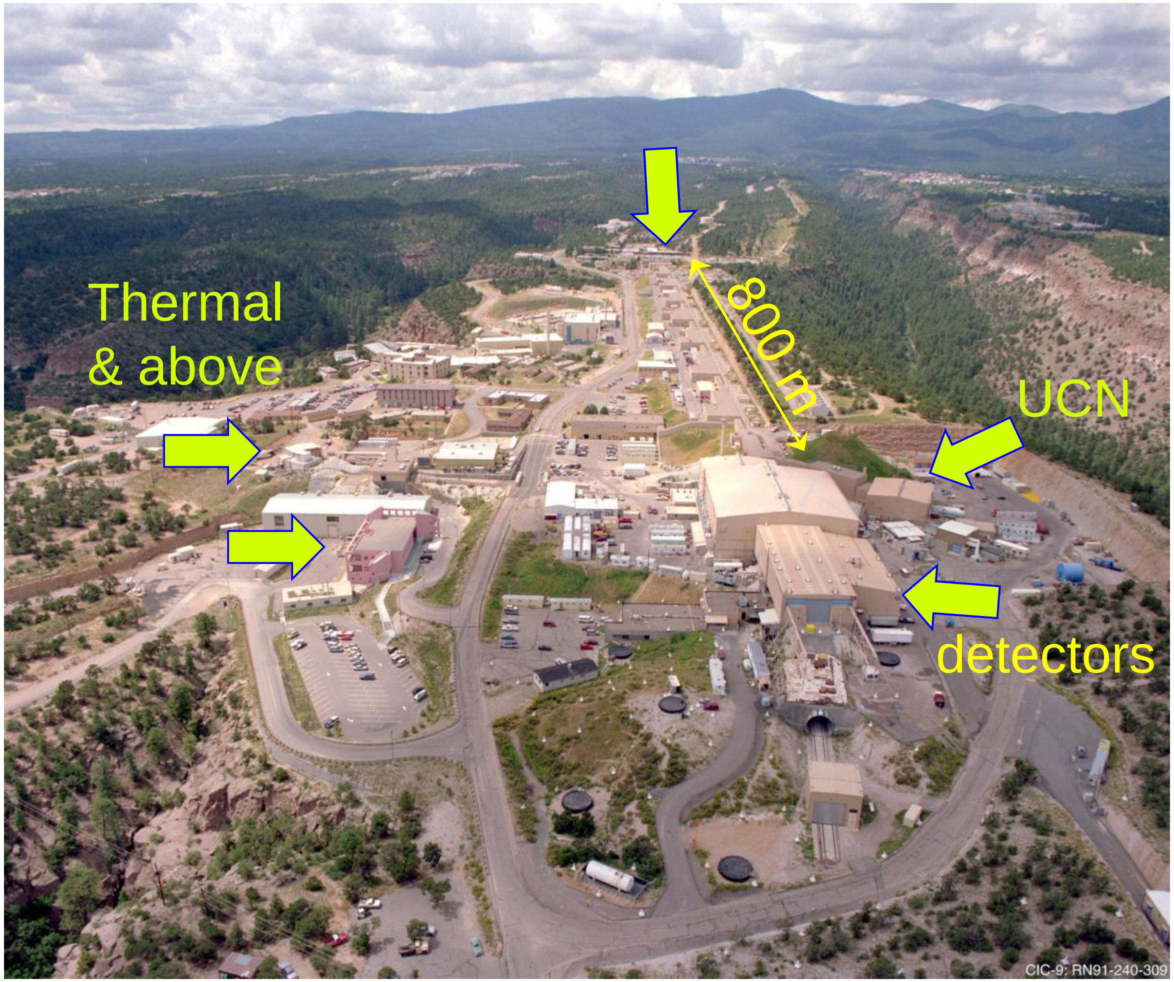
- Neutron β-decay
- Neutron EDM
- Neutron lifetime
- Matter-antimatter
- Dark matter
- …

Los Alamos Neutron Science Center (LANSCE)

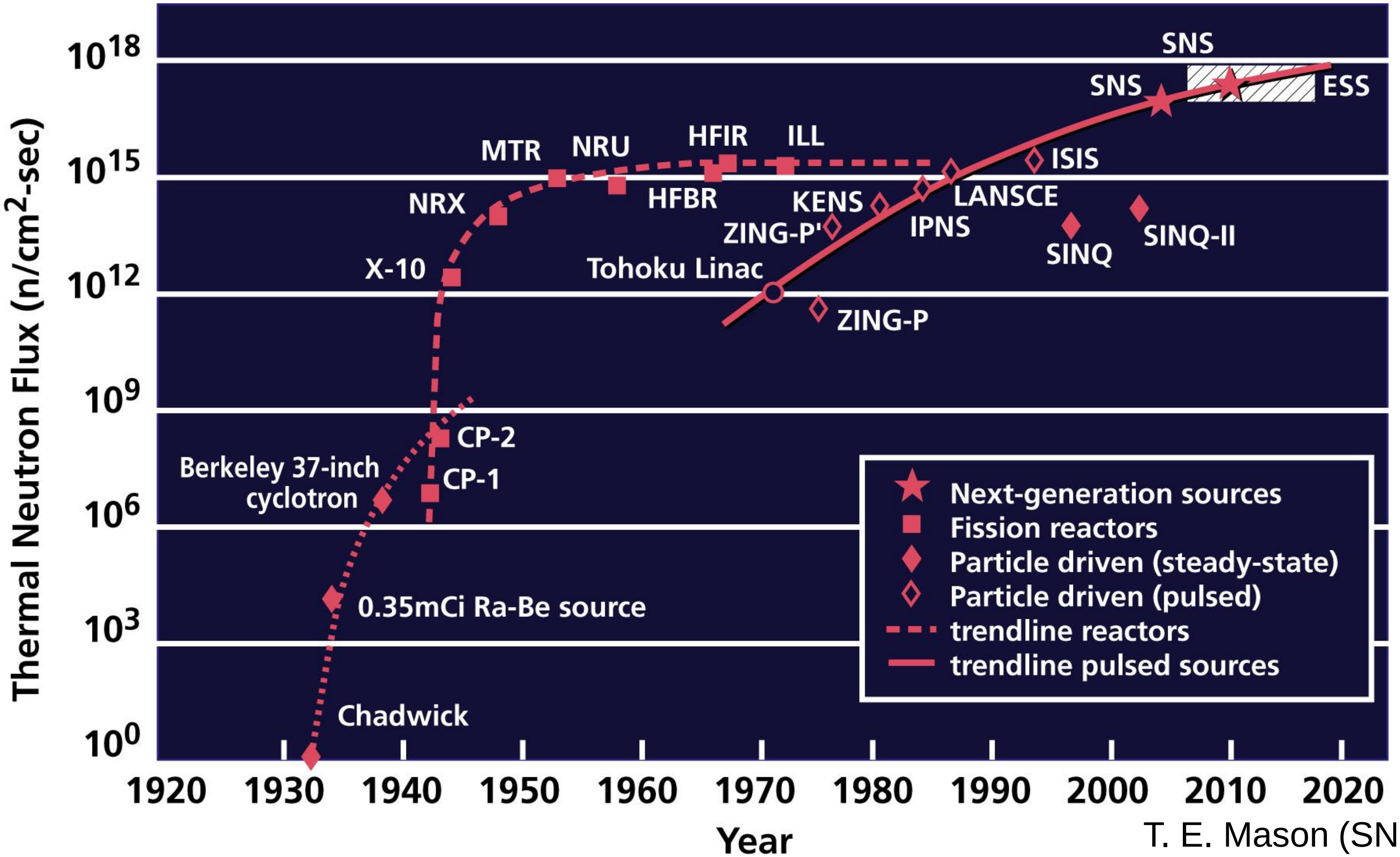








Evolution of neutron source



T. E. Mason (SNS/ORNL)

(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Outline

- Background
- **DiVincenzo criteria for UCN QC**
- UCN trapping & entanglement
- UCN source & detection

DiVincenzo criteria for Neutrons

C1: A scalable free neutron system with well characterized qubits;

- the neutron spin or spatially quantized states of neutron ('mini-traps')

C2: The ability to initialize the spin state of neutron qubits;

C3: A coherence time much longer than the operational time;

- Weak neutron interactions demonstrated.

C4: A universal set of quantum gates;

- 'mini-traps'
- Entangled free neutrons and Unitarian transformation

C5: A qubit-specific measurement;

- 'mini-traps'
- QND measurement of a free neutron

C6: The ability to interconvert stationary and flying qubits;

C7: The ability to faithfully transmit flying qubits between specified locations;

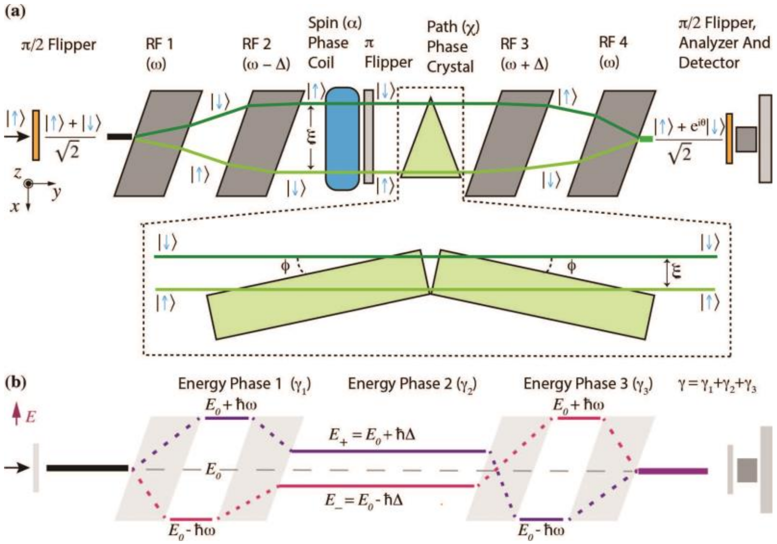
Near-term challenges

Q1: 'mini-traps' for free neutrons

Q2: QND measurement of a free neutron;

Q3: Free-neutron entanglement;

"*Unveiling contextual realities by microscopically entangling a neutron*"



Shen et al, https://arxiv.org/abs/1908.09823

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Why ultracold neutrons?

Material:	V_F[8]	v_C[9]	η (10^{-4})[9]
Beryllium	252 neV	6.89 m/s	2.0-8.5
BeO	261 neV	6.99 m/s	
Nickel	252 neV	6.84 m/s	5.1
Diamond	304 neV	7.65 m/s	
Graphite	180 neV	5.47 m/s	
Iron	210 neV	6.10 m/s	1.7-28
Copper	168 neV	5.66 m/s	2.1-16
Aluminium	54 neV	3.24 m/s	2.9-10

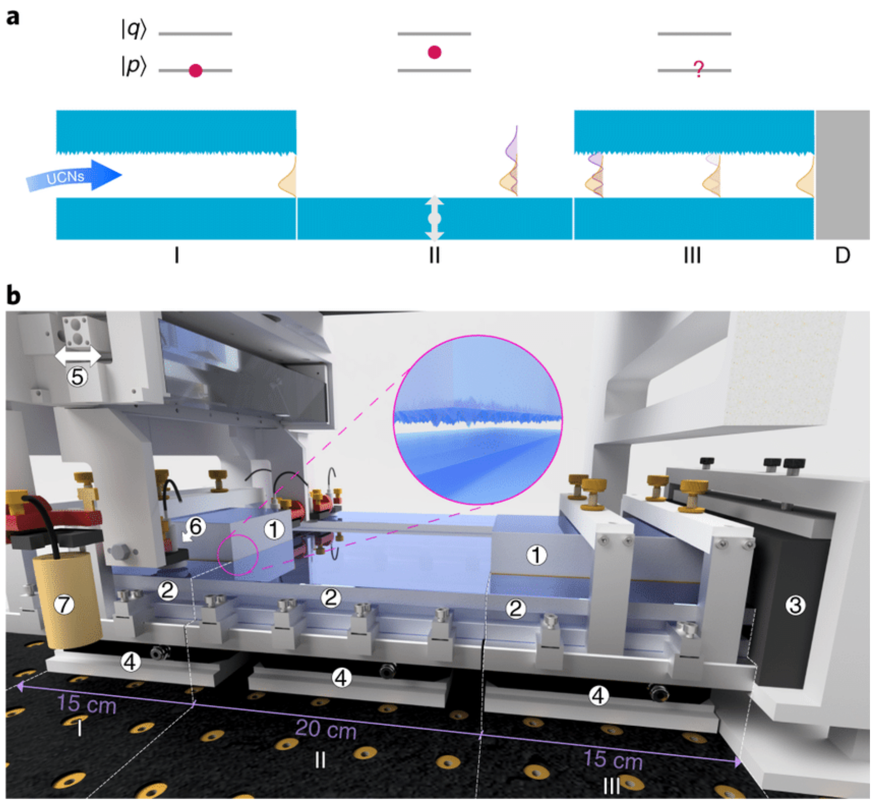
Fermi potential

^{58}Ni = 335 neV

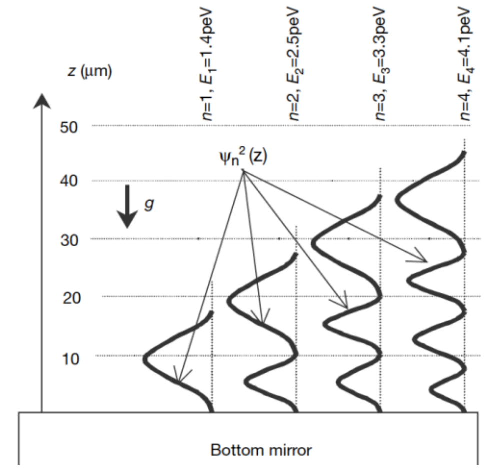
Gravity: 1 m ~ 102 neV
Magnetic field: 1 T ~ 60 neV

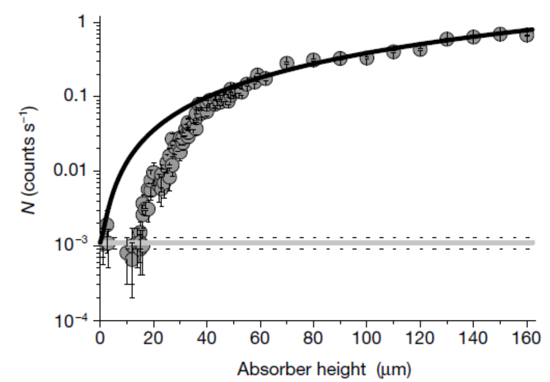
The state of the art

~ 3 m/s



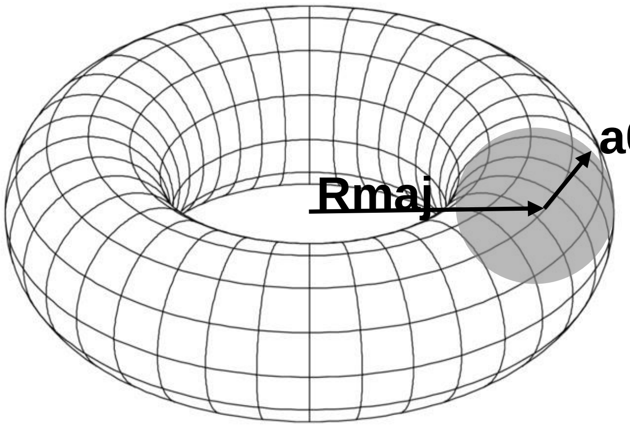
Cronenberg et al, Nature Phys. (2018)



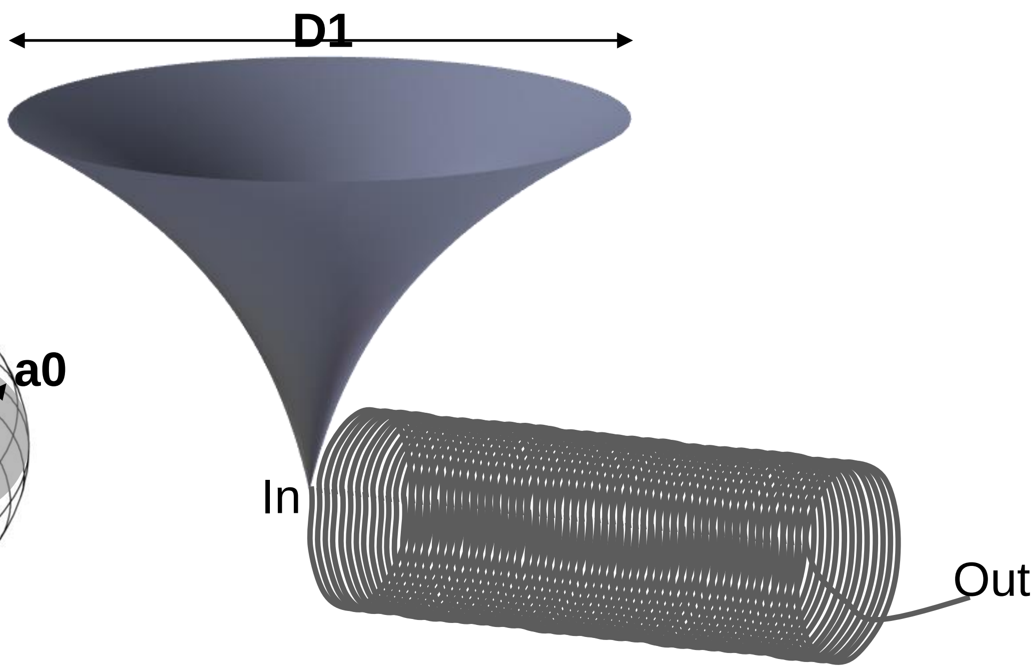


Nesvizhevsky et al, Nature (2002)

Minitrap concepts

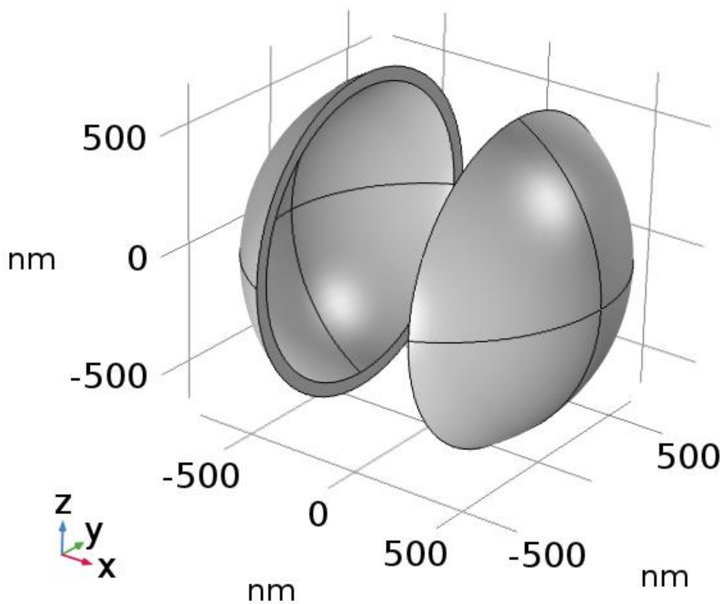


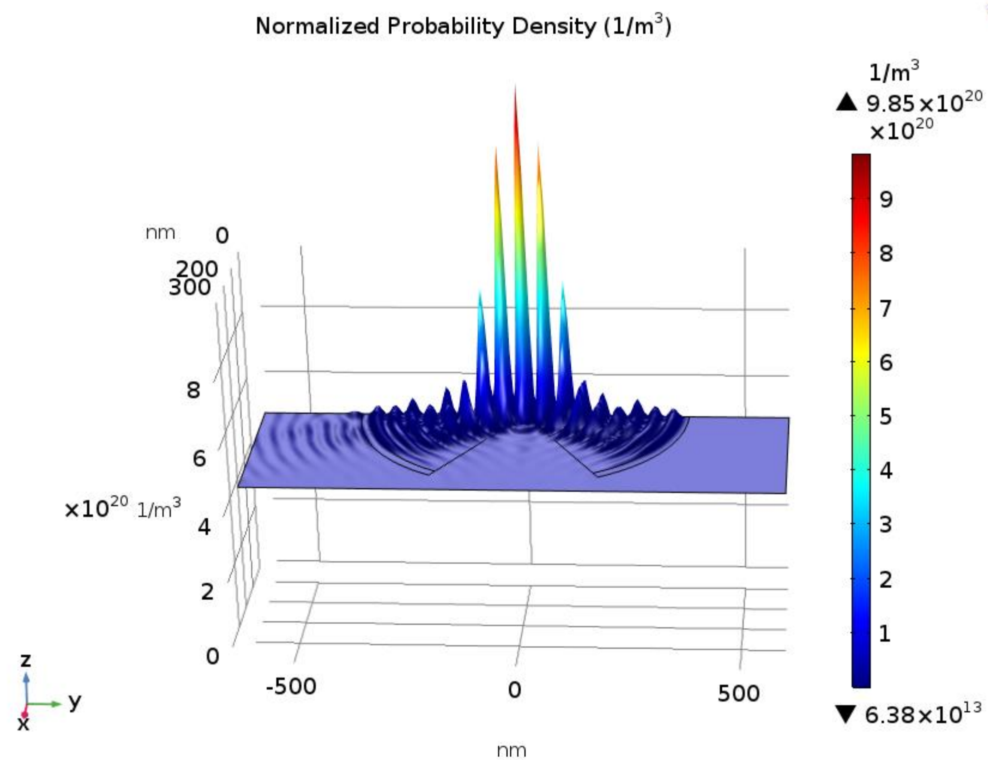
UCN racetrack



UCN fiberguide (~ 1 km long)

Minitrap concepts: nanocavity





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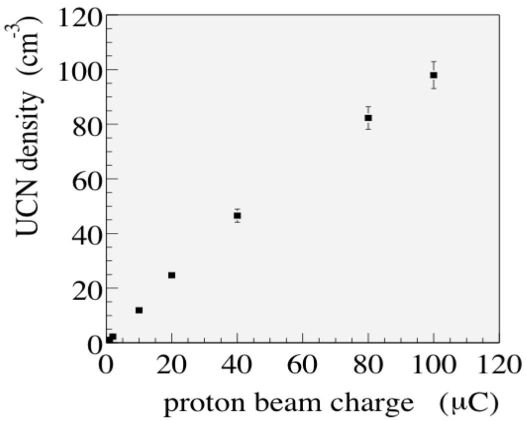
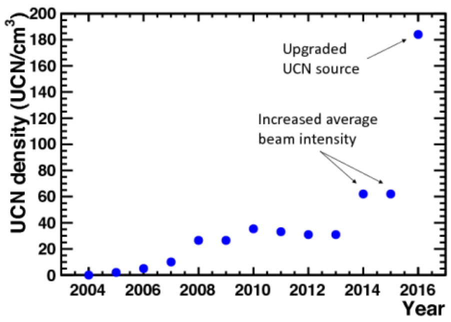
- **UCN source & detection**

The LANL UCN Source

C. Morris et al., PRL 89, 272501 (2002)





T. Ito et al., PRC (2018)

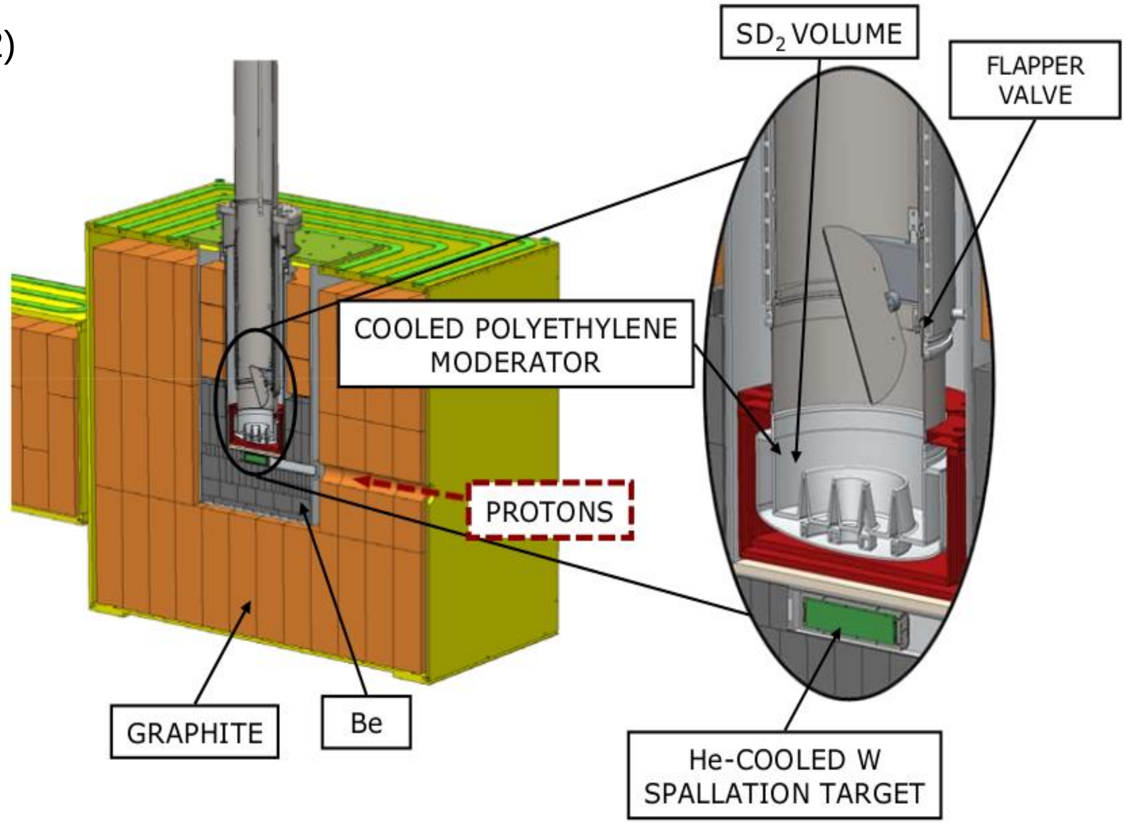


Image credit: UCN collaborations

UCN science → Physics beyond the Standard Model

- Neutron EDM
- Neutron β-decay
- Neutron lifetime
- Dark matter
- …

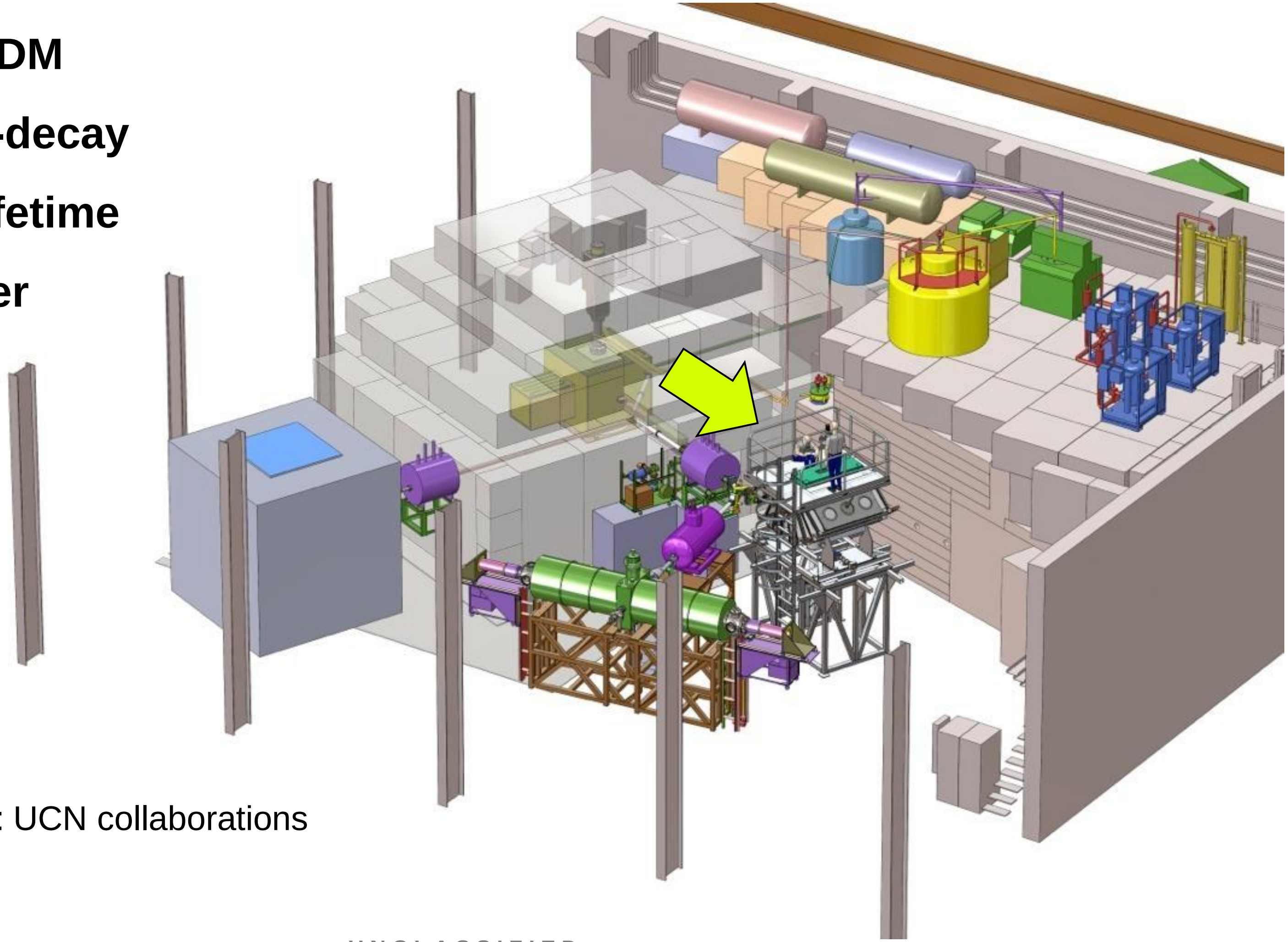
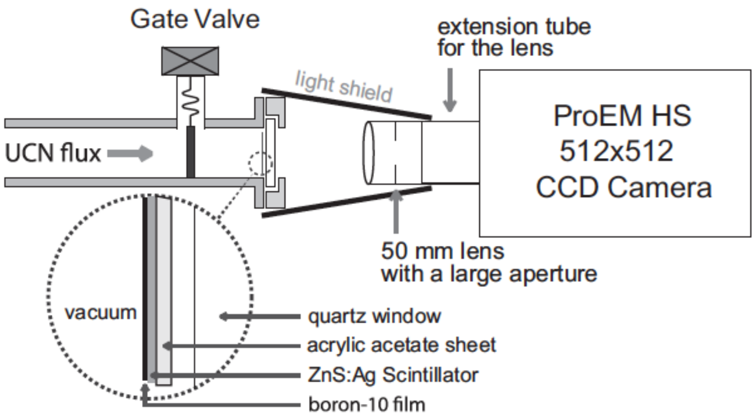


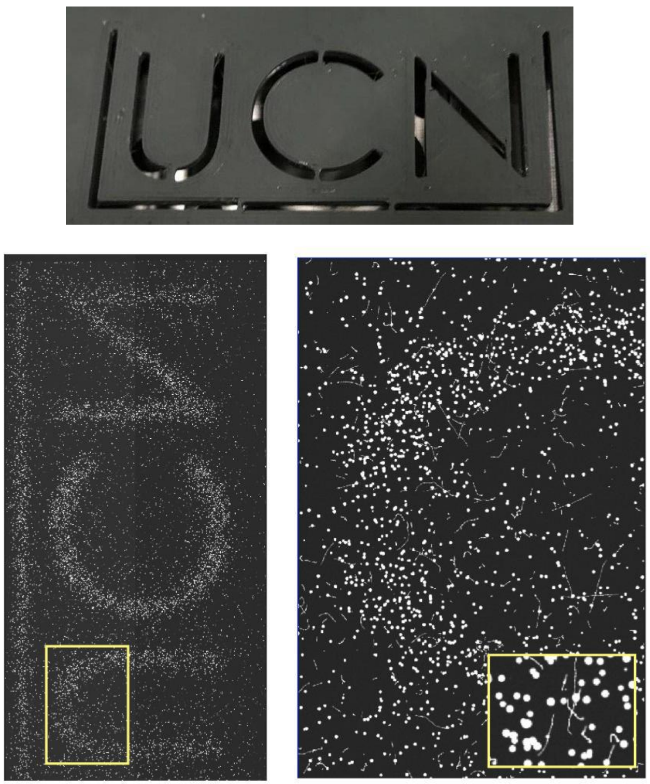
Image credit: UCN collaborations

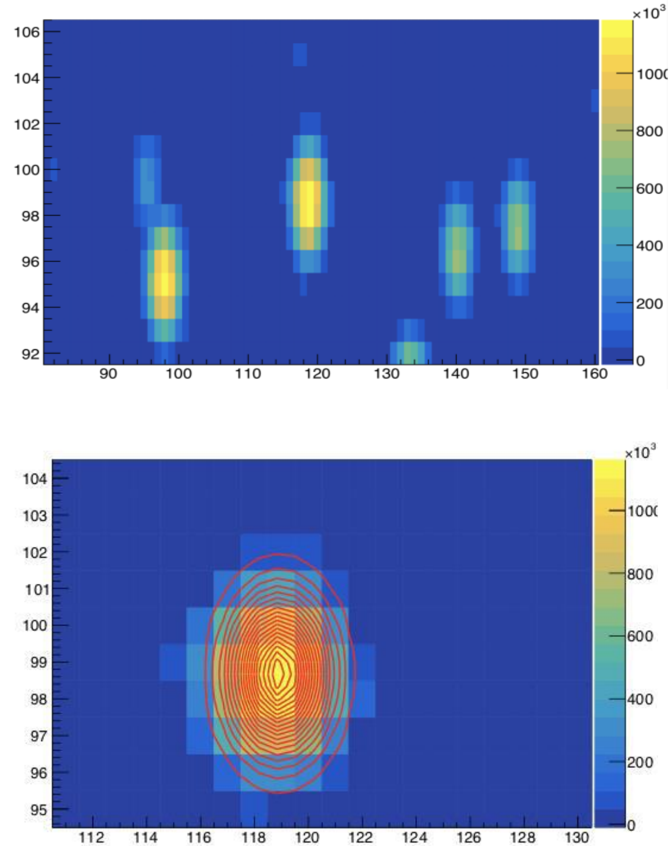
Seeing individual UCN using CCD cameras



W. Wei et al, NIMA 830 (2016) 36-43.

Improved resolution meeting quantum state needs





K. Kuk et al, https://arxiv.org/abs/1903.01335 (2019).

QND of single photons

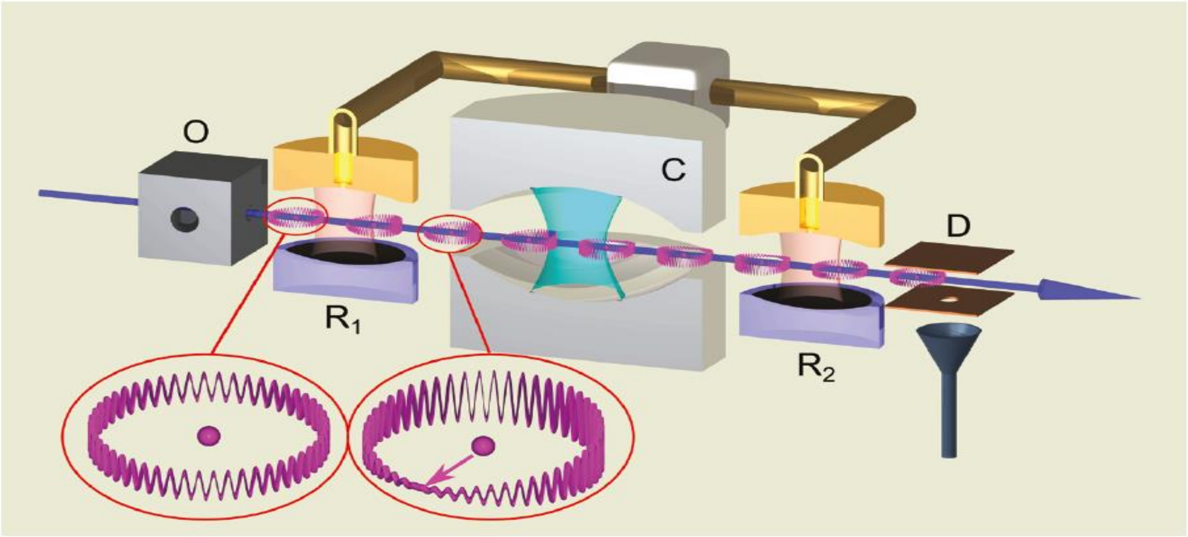
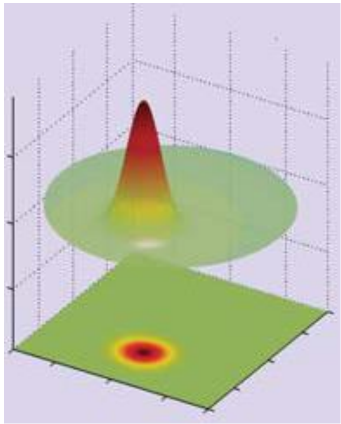
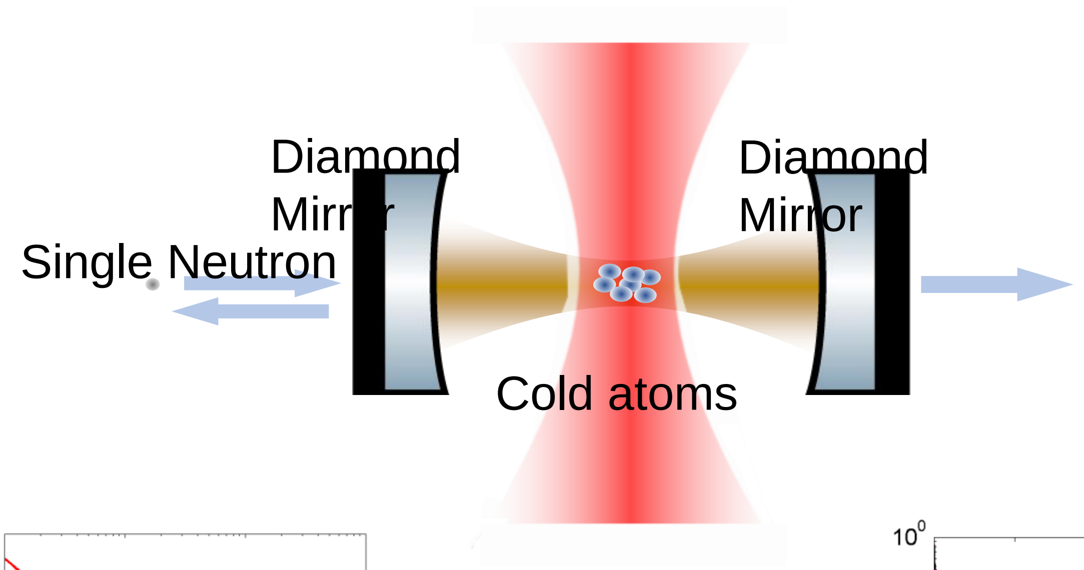


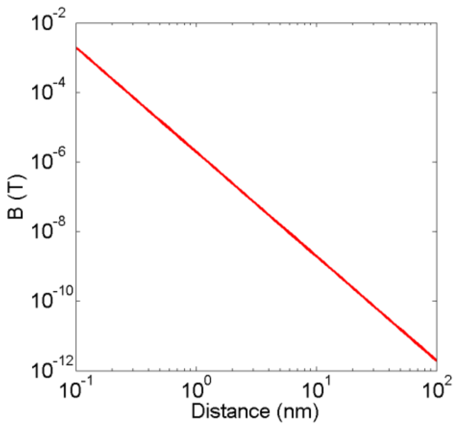
FIGURE 10. The Cavity QED Ramsey interferometer set-up. The insets show sketches of the circular atom in an energy eigenstate (left) and in a superposition state after interaction with the microwave pulse in R_1 (right). (Reprinted with permission from [49], © American Physical Society).

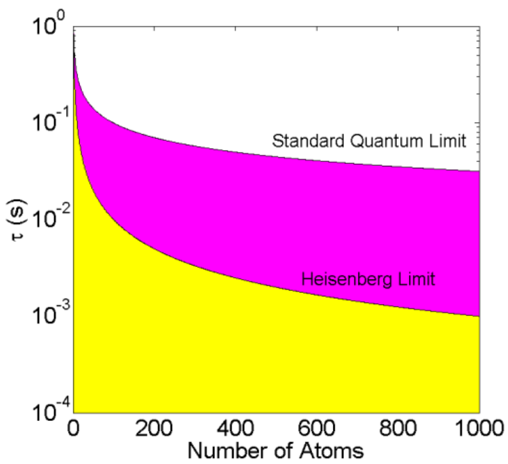


Haroche et al, Phys. Today (2013)

QND of a free neutron difficult yet feasible







Summary

- A UCN quantum computer(QC) is theoretically allowed
- Technology development can be broken down into multiple key components
- LANSCE and other assets at LANL provide solid foundation for UCN QC demonstration

The UCNτ Collaboration

Indiana University/CEEM
E. R. Adamek, N. B. Callahan, W. Fox, C.-Y. Liu, G. Pace, D. J. Salvat,
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